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Modeling of environmental aspects related to reverse osmosis desalination supply chain

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Abstract

Background: This study aimed to model optimization of strategic environmental management decisions in the operation of reverse osmosis desalination, emphasizing the costs required for the environmental protection during the production of freshwater using reverse osmosis technology.

Methods: This analytical research was conducted in five cities of Hormozgan province in Iran for 18 months from February 2018 to September 2019. The research includes eight phases of defining the research problem, data collection, preliminary data analysis and decision criteria, mathematical modeling, model validation, information preparation, analysis and finally discussion, conclusions and suggestions. The main environmental issues were the carbon dioxide (CO_2) release rate due to power demand and rejected brine water (RBW) were entered the mathematical model.

Results: The desalination plants of Abu Musa, Bandar Abbas, Qeshm, Sirik, and Hormoz with water production flow rate of 2100, 89 000, 5300, 3300 and 1500 m^3/d can generate 2360.82, 100053.80, 5958.260, 3709.86 and 1686.30 tons/year of CO_2 emissions respectively. This output requires 1.35, 57.47, 3.42, 2.13 and 0.97 million USD for controlling the process, respectively. For reduction of the negative effect of RBW 0.75, 22.79, 1.78, 1.15 and 0.55 million USD respectively, is needed.

Conclusion: Recommendations for environmental impacts protection of RBW, for desalination capacity up to 50 000 m^3/d, are; (a) for desalination capacity up to 50 000 m^3/d; dilution the RBW using raw water before entering into the sea, (b) for capacity of 50 000-100 000 m^3/d; dispersing RBW in sea using diffuser, and (c) for capacity more than 100 000 m^3/d; hybrid water desalination plants and power plant. Application of power plant cooling water to dilute RBW may reduce cost.

Keywords: Mathematical modeling, Freshwater, Osmosis, Brine, Seawater.

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Introduction

Although water accounts for about 71 % of the earth surface, freshwater scarcity is one of the most important worldwide issues. Oceans and seas contain about 97.5% of total water, while freshwater is only 2.5%, of the total, more than 68% is locked up in polar ice and glaciers, and the rest "30%" is groundwater (1). Iran's renewable water resources are estimated to be 110 to 130 billion cubic meters per year. With a population of more than 80 million, the country's per capita renewable water is less than 1700 cubic meters per year. With any of the internationally accepted indices, Iran is in the state of water stress and dehydration which necessitates the use of desalination.

The worldwide capacity for desalination projects increased dramatically from 326 cubic meters per day in 1945 to more than 95.6 million cubic meters per day in 2016 (2). Among the existing desalination technologies, reverse osmosis membrane technology accounts for 66% of the capacity utilized, followed by multi-stage flash and multi-effect distillation with 20% and 7% of the capacity utilized, respectively (3). Seawater accounts for 58% of the world's desalination water feed (4).

Environmental impacts of seawater reverse osmosis (SWRO) desalination can be broadly classified into three categories, including energy consumption which releases carbon dioxide (CO_2) into the atmosphere, intake and brine discharge (5,6). Desalination effluent results in known environmental effects on seagrass habitats and phytoplankton, invertebrates and fish communities in areas surrounding effluent discharge (7,8). Overall, enclosed and shallow sites with abundant marine organisms are more sensitive to effluent discharge than the offshore sites capable of diluting and dispersing plant rejected water (2,9).

The previous studies have shown the variable effects of desalination plants on the salinity of the received water. Based on the studies, the effects of saline effluent discharge can be observed for tens or hundreds of meters (10,11), or in extreme cases, several kilometers from the effluent discharge site (12). Few studies on the environmental issues of intake and brine discharge of SWRO, have shown that proper design of SWRO based on the environmental impact analysis, can minimize the environmental impacts and the costs of environmental protection for desalination plants were analyzed (5,13-16).

Most of the above-mentioned models focused on optimizing the economic dimension of water supply systems and often overlook the details of the environmental aspects. This research expanded the economic model presented by Al-Nory et al (17) regarding the water supply chain of the desalination plant by emphasizing environmental details. Environmental details include modeling the reduction of salinity and chemical components of the rejected brine water (RBW) from plants by diluting the effluent before being entered the sea according to a standard that permits discharge into the receiving water. Note that, CO_2 emissions have also been modeled as an environmental impact. Desalination supply chain activities include obtaining feed water and chemicals needed for the desalination processes, desalination process systems, water storage and distribution of freshwater to end-users (18). The importance of examining the economic and environmental impacts of water purification using desalination technology and the provision of desalinated water allows decision-makers to examine the system as a whole (19). For instance, any delay in the distribution of water from storage tanks to consumers could disrupt the desalination process and affect the overall performance of the desalination water supply chain. In this study, due to the importance of environmental issues in terms of produced water costs and environmental protection aspects, this subject is evaluated and modeled in Hormozgan province as the center of the desalination of Iran.

Materials and Methods

This analytical research is conducted in 5 cities of Bandar Abbas, Qeshm, Hormoz, Sirik, and Abu Musa in Hormozgan province (Figure 1) for 18 months from February 2018 to September 2019. In addition, the operational and environmental data of desalination plants for a period of past 20 years were obtained from the Hormozgan Water and Wastewater Company; then entered in the model and analyzed.

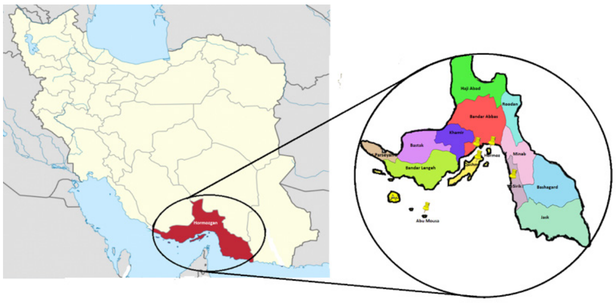

Figure 1. The locations of studied desalination plants.

The study plan was classified into eight phases encompassing: 1) Defining research problem, 2) Data collection, 3) Preliminary data analysis and decision criteria, 4) Mathematical modeling, (5) Model validation, 6) Information preparation, 7) analysis and 8) Discussion, Conclusions and suggestions.

In the present study, the typical SWRO plants are studied. The main parts of typical SWRO plants are included in the Intake section, pretreatment (generally coagulation and granular filter), high-pressure pumps and membrane modules. After that, a post-treatment unit is located to add some minerals to the RO water product (Figure 2). Modeling fundamental data include the rate of raw water intake, water production, and brine water flow rate, type of discharge into receiving waters, and investment cost and operating costs such as the consumed power used chemicals, manpower, and the other economic and environmental aspects.

To evaluate the CO_2 production, since the power generation model in Iran is almost similar to the water production by desalination, the mathematical model of electricity production in Iran is used to estimate the amount of CO_2 emitted from desalination plants(20,21) Since the power generation model in Iran is almost similar to the Portuguese power generation model collected from the literature (21), this model was used to estimate the amount of greenhouse gas CO2 required by the mathematical model.

Model parameters

In this analysis, a mathematical model is employed which its parameters are shown in Table 1. Note that the model is based on AL-Nory et al (17) and Balfaqih et al (1).

Decision variables

Decision variables for the production and investment in desalination plants and transmission lines presented in Table 2.

The total cost of water (TWC) is often cited in the literature of the desalination industry as a common comparison between projects. Table 3 shows comparative evaluation of the total cost of the objective functions and their components per cubic meter of freshwater.

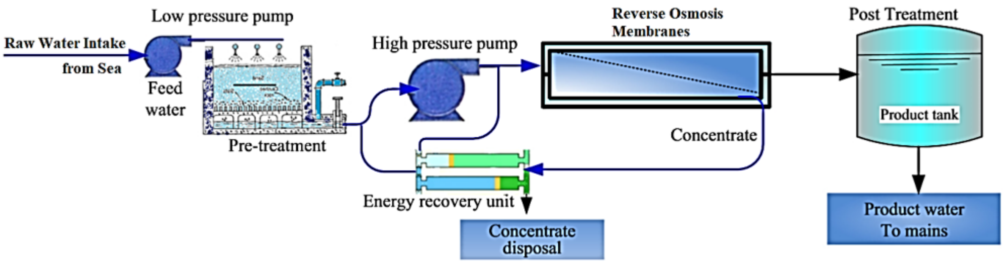

Figure 2. Simple diagram of a typical reverse osmosis desalination plant (20).

Target function optimization

The objective function specified in Eq (1), minimizes the total investment cost and supply chain operation of both the plant and the transmission line. Furthermore, it minimizes environmental impacts.

$$minTC = \sum_{l \in N^s} c_l^T + c_l^{enviT} + \sum_{i \in E} c_i^N \qquad (1)$$

Model limitations

The model has a few limitations. Equation (2) represents the net present value (NPV) of the total investment cost (CAPEX) of the plant at the location (l).

$$v_l^c = \sum_{t \in T_l} \frac{cpx_{lt}^T * y_{lt}}{(1 + int)} \qquad \forall \quad l \in Ns \qquad (2)$$

Equation (3) represents the NPV of the operation cost at the location (l) in the time of (h).

$$v_{lh}^o = \sum_{t \in T_l} \frac{opx_{lt}^T * (1 + \inf)^h * x_{lth}}{(1 + int)^h} \quad \forall \quad l \in Ns, h \in H \qquad (3)$$

Table 1. Mathematical model parameters used in the study

Parameter	Definition
Inf	Inflation rate
Int	Interest rate
cpx_{lt}^{T}	Estimation of investment cost for factory (t) at location (l) at time (0)
v_{lh}^{o}	Net present value (NPV) of the total operating costs (OPEX) of the factory (t) at the location (l) in time horizon (h)
$aopx_{lt}^{T}$	Estimation of annual operating costs of plant (t) at location (l)
opx^{T}_{lt}	Estimation of the first-year operating costs for each cubic meter of a desalination plant at the location (l)
v^{r}_{l}	The value of the plant's rotation at the location (l) at the end of the planning period
cpx_{i}^{N}	Estimated the total investment costs per year for each transmission line (i)
W^{o}_{ih}	NPV total operating costs in the year of zero (OPEX) in Network time of (h)
$aopx_{i}^{N}$	Annual operating cost estimates (OPEX) at transmission line (i)
opx_{i}^{N}	Estimation of the first-year operating costs per cubic meter of water at transmission line (i)
cap^{T}_{t}	Desalination plant design capacity (m^3/d) $t \in T$
cap_{i}^{N}	Transmission line capacity (m^3/d) $i \in E$
E^{s}_{l}	Plant Outlet Pipe Set $l \in N^s$
E^{in}_{l}	The sum of input influents to the aggregator in place $l \in N^a$
E^{out}_{l}	The output stream of the collector at the location $l \in N^a$
d_{lh}	Demand in place $l \in N^d$ at the time of (h)
cf_{lth}	Plant capacity $t \in T_l$ at the location $l \in N^s$ at the time of $h \in H$
u^{co2}_{lt}	CO_2 emissions produced by the plant (t) at the location (l) for one cubic meter of water (Kg CO_2/m^3)
Er_{lt}	Power required by the plant (t) in (kwh/m^3)
Ef	CO_2 emission factor (CO_2 kg-e/kwh)
opx CO_2	CO_2 cost (\$/kg CO_2)
Pc	The v^c_l coefficient as the percentage of the total investment cost for the effluent dilution cost
Po	The v_{lh}^o coefficient as the percentage of the total investment cost for the effluent dilution cost

Table 2. Decision variables for the production and investment in desalination plants and transmission line

Decision Variables	Description
Xlth	The rate of produced water in the plant at the location (l) at time of (h) whenever l∈Ns ‹t∈Tl and h∈H; except year (0)
Ylt	The number of (t) plants installed at the location (l) whenever t∈Tl, l∈Ns
Zih	The current rate in the transmission line (i) at the time (h) whenever i∈E and h∈H
Vcl	Net present value (NPV) of the total investment costs (CAPEX) for the plant at the location (l)
cTl	NPV of the total plant costs at the location (l)
Wci	NPV of the total investment costs (CAPEX) at water transmission line
cNi	NPV of the total transmission line cost (i)
ulCO2	Total emissions of CO_2 at the location (l) per year
Opxul CO_2	NPV of the total costs of CO2 emission at the location (l)
Clred TDS &chem	NPV of the total effluent dilution costs to reduce TDS and effluent chemical concentrations
clenviT	NPV of the total environmental costs of the desalination plant at the location (l)

Equation (4) represents the NPV of the residual value of the plant at the location (l) at the end of the design period.

$$v_l^r = \sum_{t=T_l} \frac{ndp_{lt} * (1+inf)^{|H|+2} * y_{lt}}{(1+int)^{|H|+2}} \quad \forall \quad l \in Ns \qquad (4)$$

Equation (5) represents the NPV of the total cost of the plant at the location (l).

$$c_l^T = v_l^c + \sum_{h \in H} v_{lh}^o - v_l^r \quad \forall \quad l \in N^s \qquad (5)$$

Equation (6) represents the NPV of the total investment cost (CAPEX) of the transmission line at the location (l).

$$w_i^c = \frac{cpx_i^N}{(1+int)} \quad \forall \quad i \in E \qquad (6)$$

Equation (7) represents the NPV of the total operational costs (OPEX) for the transmission line at time (h).

$$w_{ih}^o = \frac{opx_i^N * (1+inf)^h * z_{ih}}{(1+int)^h} \quad \forall \ i \in E \qquad (7)$$

Equation (8) represents the NPV of the total costs for the transmission line.

$$c_i^N = w_i^c + \sum_{h \in H} w_{ih}^o \quad \forall \ i \in E \qquad (8)$$

The binary variable is the establishment or non-establishment of the plant as Eq (9). Moreover, the binary variable is the establishment or non-establishment of the transmission line as Eq (10).

Y_t = 0 or 1 (9)
Y_i = 0 or 1 (10)

Equation (11) shows the water produced rate by the plant (t) at the location (l) in the time horizon (h) limited by the plant capacity at the location (l) with the cfl_{th} capacity coefficient.

$$x_{lth} \le cap_t^T * cf_{lth} * 365 * y_{lt} \quad \forall \quad l \in Ns, t \in Tl, h \in H \qquad (11)$$

Equation (12) denotes the amount of freshwater that responds to the locations water demand at location (l) in the time period (h), which is equal to or greater than the demand.

$$\sum_{i \in E_l^d} z_{ih} \ge d_{lh} \quad \forall \quad l \in Nd, h \in H \qquad (12)$$

Equation (13) shows the amount of fresh water entered into and out of the aggregator; input amount is equal to the output.

$$\sum_{i \in E_l^{in}} z_{ih} = \sum_{i \in E_l^{out}} z_{ih} \quad \forall \quad l \in N^a, h \in H \qquad (13)$$

The total amount of water produced by the desalination plant (t) at the location (l) enters the transmission line according to Eq (14).

$$\sum_{t \in T_l} x_{lth} = \sum_{i \in E_l^s} z_{ih} \quad \forall \quad l \in Ns, h \in H \qquad (14)$$

The flow rate of water at the transmission line (i) at the time (h) is limited to the capacity of the transmission line (i) and is as Eq (15).

$$z_{ih} \le cap_i^N \quad \forall \quad i \in E, h \in H \qquad (15)$$

The CO_2 emission value of the desalination does not exceed the emission limit for CO_2 emissions and is as Eq (16).

$$u \le u^{max} \qquad (16)$$

The total amount of CO2 emissions at the location (l) is as Eq (17).

$$u_l^{CO_2} = \sum_{t\in T_l} x_{lth} * u_{lt}^{CO_2} \qquad \forall \quad l\in N^s \tag{17}$$

The u^{co2}_{lt}, CO_2 emissions produced by the plant (t) at the location (l) for one cubic meter of water is as Eq (18).

$$u_{lt}^{CO_2} = Er_{lt} * Ef \tag{18}$$

Where Er_{lt} is the energy required by the (t) plant kWh/m^3 and Ef is the CO_2 emission factor (kg CO_2–e/kWh). The NPV of the total cost of CO_2 emissions in the period design is (H) and is as Eq (19).

$$opxu_l^{CO_2} = \sum_{h\in H} \frac{u_l^{CO_2} \times opxCO_2 \times (1+inf)^h}{(1+int)^h} \tag{19}$$

The opx CO_2 is the cost of CO_2 in \$/kg CO_2. The NPV is the cost of diluting the brine discharge to reduce the salinity and effluent chemicals is as Eq (20).

$$c_l^{redTDS\&chem} = pc \times v_l^c + po \times \sum_{h\in H} v_{lh}^o \tag{20}$$

The NPV is the total cost of reducing the environmental impacts of the desalination plant which is expressed in Eq (21).

$$c_l^{enviT} = opxu_l^{CO_2} + c_l^{redTDS\&chem} \tag{21}$$

The cost of operating one cubic meter of water at the opx_{lt}^T plant is presented in Eq (22).

$$opx_{lt}^T = \frac{aopx_{lt}^T}{cap_t^T \times cf_{lth} \times 365} \tag{22}$$

Remark that the capacity of the cap^T_t plant is expressed as m^3/d. The coefficient capacity of cf_{lth} is considered for the plant of $t\in T_l$ at the location of $l\in N^s$ at time $h\in H$. The estimation of the opx_i^N operating costs per cubic meter of water in the transmission line i is as Eq (23).

$$opx_i^N = \frac{aopx_i^N}{cap_i^N * 365} \tag{23}$$

Remark that the capacity of the transmission line cap_i^N is expressed as m^3/d. The total cost of the water supply chain (TWC) for comparing the objective functions and its components per cubic meter of freshwater is as follows. To make the target functions understandable and comparable, it is expressed in terms of TWC, the total cost per cubic meter of freshwater (US\$/m^3).

TWC_1 plant. Total Investment, operation and environmental costs (Salinity Reduction + CO_2) as US\$/m^3 of freshwater as Eq (24).

$$TWC_1 = \frac{\sum_{l\in N^s} c_l^T + c_l^{enviT}}{\sum_{h\in H} x_{lth}} \tag{24}$$

TWC_2 plant. Total Investment, operating and environmental costs (for the salinity reduction) without CO_2 control cost as US\$/m^3 of freshwater as Eq (25).

$$TWC_2 = \frac{\sum_{l\in N^s} c_l^T + c_l^{redTDS\&chem}}{\sum_{h\in H} x_{lth}} \tag{25}$$

TWC_3 plant. Total investment and operating, without environmental costs as US\$/m^3 of fresh water is as Eq (26).

$$TWC_3 = \frac{\sum_{l\in N^s} c_l^T}{\sum_{h\in H} x_{lth}} \tag{26}$$

TWC_4 for transmission line. Total investment and operating costs as US\$ /m^3 of fresh water is as Eq (27).

$$TWC_4 = \frac{\sum_{i\in E} c_i^N}{\sum_{h\in H} x_{lth}} \tag{27}$$

TWC5 for plant plus transmission line. Total investment, operating and environmental costs (salinity+ CO_2) in US\$/m^3 per cubic meter of freshwater as Eq (28).

$$TWC_5 = \frac{minTC}{\sum_{h\in H} x_{lth}} \tag{28}$$

TWC6 for plant plus transmission line. Total investment, operating and environmental costs (salinity reduction) without CO_2 control in US\$/m^3 per cubic meter of freshwater is as Eq (29).

$$TWC_6 = \frac{\sum_{l\in N^s} c_l^T + c_l^{redTDS\&chem} + \sum_{i\in E} c_i^N}{\sum_{h\in H} x_{lth}} \tag{29}$$

TWC7 for plant plus transmission line. Total investment and operating without environmental costs in US\$/m^3 of freshwater is as Eq (30).

$$TWC_7 = \frac{\sum_{l\in N^s} c_l^T + \sum_{i\in E} c_i^N}{\sum_{h\in H} x_{lth}} \tag{30}$$

TWC8 environmental. The cost of (CO_2 + salinity reduction) in US\$/m^3 of fresh water is as Eq (31).

$$TWC_8 = \frac{\sum_{l\in N^s} c_l^{enviT}}{\sum_{h\in H} x_{lth}} \tag{31}$$

WC9 environmental. The cost (CO_2) in US\$ /m^3 of fresh water is as Eq (32).

$$TWC_9 = \frac{\sum_{l\in N^s} opxu_l^{CO_2}}{\sum_{h\in H} x_{lth}} \tag{32}$$

TWC_{10} environmental. The cost (salinity reduction) in US$/m^3 of fresh water is as Eq (33).

$$TWC_{10} = \frac{\sum_{l \in N^s} c_l^{redTDS\&chem}}{\sum_{h \in H} x_{lth}} \quad (33)$$

Based on the previous studies, the total cost of a carbon tax was ranging from \$19 per ton (22) to \$23 per ton (23). In this study, it is estimated at \$23 per ton or \$0.023 per kilogram of CO_2. According to the standards of Iran Environmental Protection Agency (EPA), a maximum of 10% salinity in the receiving water into discharge the effluent is allowed (24). The effluent dilution cost is estimated as a percentage of the total cost of operating and operating for desalination plant. The mathematical model is then coded in MATLAB software and solved using an opti-intlinprog solver from the OPTI Toolbox. By changing the parameters, the sensitivity analysis of the designed model is presented.

Results

The model for the existing water desalination supply chain in the cities of Abu Musa, Bandar Abbas, Dargan Qeshm, Sirik, and Hormuz is solved based on the data collected during 20 years and presented in Table 3. The model output decision variables are presented in Table 4. Comparative evaluation of the total cost of objective functions and their components in terms of cubic meters of fresh water is also illustrated in Figure 3.

Discussion

The function of "environmental target" is investigated in two parts including environmental impacts of CO_2 emissions and environmental effects of saline effluent disposal. For desalination supply chain in Bandar Abbas, Total TWC 5, TWC 3, plant, TWC 4, transmission line TWC 9 CO_2, TWC 10 Wastewater dilution are 0.5334, 0.3640, 0.0458, 0.0885 and 0.0351 US$/m^3 respectively, presented in Figure 4.

Environmental costs of CO_2 emissions control

Increased use of fossil fuels for desalination can increase air pollution caused by CO_2 emissions and cause damage to public health and the environment. For energy consumption of 4 kW/m^3, the portion of environmental costs related to CO_2 emissions is computed by about 16.59% which equals to 0.0885 US$/m^3 (Table 5). As shown in Table 6, the Bandar Abbas desalination plant with a nominal and actual capacity of 100 000 and 89 000 m^3/d respectively, annually produces 10 008 800 kg CO_2, assuming 4 kW of energy consumption per a cubic meter fresh water production. Reducing energy consumption leads to a reduction in the amount of CO_2. With more efficient utilization and energy recovery, energy can

Table 3. Mathematical model inputs; Interest rate 0f 18%, Inflation rate of 20% and time period of 20 year; (Ef= 0.77(CO_2 kg-e/kWh), cf_{lth}=0.9, Er_{lt}=4 kWh/m^3, opx $CO_{2=}$ 0.023 US$ / kg CO2, Pc= 0.15, Po=0.07)

Input parameter		Unit	Hormoz	Sirik	Qeshm	Bandar Abbas	Abu Musa
Desalination	cap^T_t	M^3/d	1750	3750	6000	100 000	2500
	cpx_{lt}^T	US$	2 300 000	4 500 000	6 600 000	80 000 000	3 000 000
	$aopx_{lt}^T$	US$	160 000	340 000	550 000	7 300 000	230 000
Transport line	Lenght	km	4	8	2	28	5
	cap_i^N	M^3/d	1750	3750	6000	100 000	2500
	cpx_i^N	US$	1 000 000	870 000	2 120 000	22 000 000	1 400 000
	$aopx_i^N$	US$	55 000	43 000	60 000	500 000	50 000
Demand	d_{lh}	M^3/d	1500	3300	5300	89 000	2100

Table 4. Model output decision variables

Decision Variables	Unit	Hormoz	Sirik	Qeshm	Bandar Abbas	Abu Musa
x_{lth}	m^3/d	1500	3300	5300	89000	2100
y_{lt}	no	1	1	1	1	1
z_{ih}	m^3/d	1500	3300	5300	89000	2100
v^c_l	US$	1949152.54	3813559.32	5593220.34	67796610.17	2542372.88
c^T_l	US$	5421556.78	11464138.19	18118363.08	236489778.17	7468877.62
w^c_i	US$	847457.63	737288.14	1796610.17	18644067.80	1186440.68
c^N_i	US$	2024722.98	1682239.80	3120141.83	29756739.28	2235277.09
u_l^{CO2}	Kg	1686300.00	3709860.00	5958260.00	100053800.00	2360820.00
$opxu_l^{CO2}$	US$	968547.98	2130805.56	3422202.87	57467180.29	1355967.18
$c_l^{redTDS\&chem}$	US$	558744.03	1153166.96	1782612.10	22788547.36	756606.29
c_l^{enviT}	US$	1527292.02	3283972.52	5204814.98	80255727.65	2112573.47

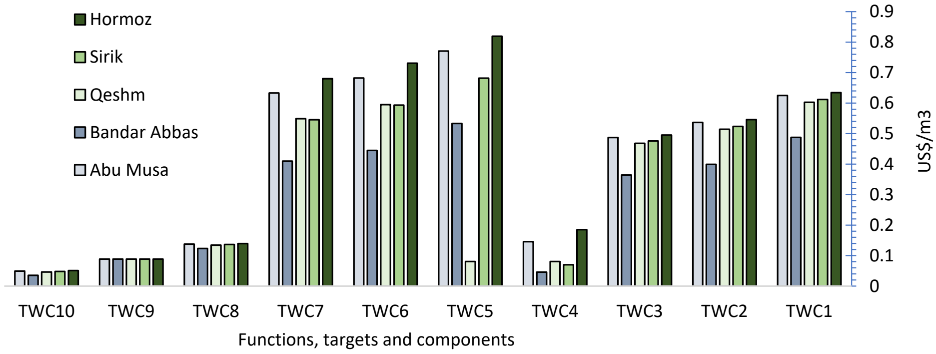

Figure 3. Comparative evaluation of the total cost of objective functions and their components in terms of cubic meters of freshwater.

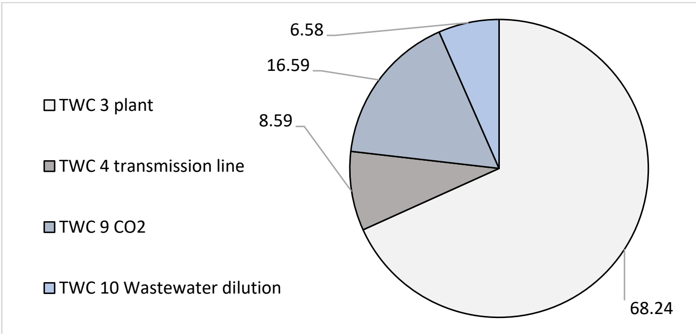

Figure 4. Supply chain cost (US$/m^3) portion of environmental costs for water desalination in Hormozgan, Bandar abbas.

be reduced to some extent to descent CO_2 emissions. However, the main solution is to use renewable energy instead of fossil fuels.

Dilution costs to reduce environmental impacts

The desalination plants use significant amounts of chemicals for the pre-treatment of saline and freshwater (25). Excessive salinity of effluent and discharge of large quantities of chemicals into coastal waters results in ecological imbalance and have major effects on receiving waters. To address environmental concerns related to effluent discharge into seawater, the concentration of chemicals and salts in the effluent should be reduced. The target function of "reducing environmental effects due to the effluent salinity" is transformed into a cost function. According to the Table 6 for dilution of different ratios of total dissolved solids (TDS) effluent to TDS receiving water, the percentages of the total cost of wastewater investment and total operating cost are estimated and entered into the model, the results of which are shown in Table 6. As shown in this table, the environmental goals are against environmental costs; hence, by higher costs, it can

Table 5. Relationship between the energy consumption and CO_2 produced in the 100 000 m^3/d desalination plant in Bandar Abbas

Erlt (kwh/m^3)	2.0	2.5	3.0	3.5	4
Ul_{CO2} (kg.CO_2)/year	50 026 900	62 533 625	74 040 350	87 547 075	100 053 800

Table 6. Relationship between environmental impacts and costs

TDS effluent/(TDS receiving water	Percentage of total investment cost	Percentage of total operating cost	TWC 2 (US$/m^3)	TWC 10 (US$/m^3)
1.05	0.20	0.10	0.4126	0.0486
1.10	0.15	0.07	0.3991	0.0351
1.15	0.10	0.05	0.3883	0.0243
1.20	0.07	0.03	0.3796	0.0156
1.25	0.03	0.01	0.3699	0.0059

meet better environmental quality related to desalination. More accurate cost estimates should be spent on a specific project and its local data. The cost of "wastewater management" is of great interest as the cost of wastewater disposal increases with the production of freshwater. The dilution cost (TWC 10) for the TDS of effluent to receiving water ratio is the US $ 0.0351/m^3. The decision-maker can attract the attention of the environmental organization according to the cost and reduce the environmental impacts. In case the ratio of TDS effluent to TDS intake water is considered to be in the standard range of 1:1, the share of dilution costs will be 7.89%, according to Figure 5.

To dilute the RBW in seawater, diffuser equipment is required, and to achieve a water flow rate of 5 to 8 meters per second, energy should be consumed. Depending on the site-specific conditions, discharge costs to the seafloor for dilution at sea are significant, typically accounting for 10 to 30 % of the total investment costs of the desalination plants (26). Previously many researches focused on supply chain management coordination and optimization challenges in different industries and circumstances (27-30). Even some scholars considered environmental and social issues in their studies (31-33).

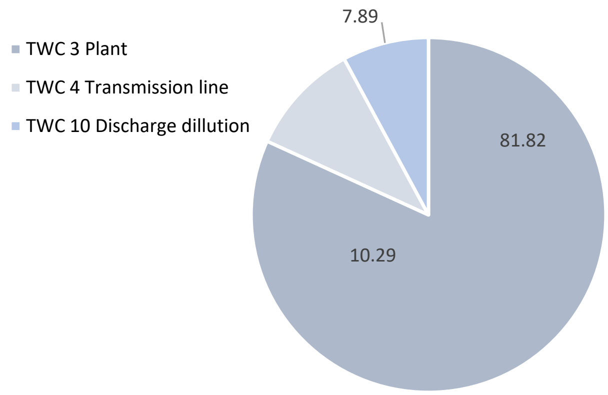

Figure 5. Costs percentage of supply chain sections including environmental costs only for wastewater dilution, without cost for CO_2 control; for TWC 6 total=0.4449 US$/m^3.

Conclusion

This study aimed to model optimization of strategic environmental management decisions in the operation of reverse osmosis desalination; emphasizing the costs required for environmental protection during the production of freshwater using reverse osmosis technology. Due to the relatively high costs of controlling environmental pollutants, unfortunately, many of these desalination plants remain neglected. The desalination plants of Abu Musa, Bandar Abbas, Qeshm, Sirik, and Hormoz with water production flow rate of 2100, 89000, 5300, 3300 and 1500 can generate 2360.82, 100053.80, 5958.260, 3709.86 and 1686.30 tons of CO_2 emissions per year respectively.

This environmental cost model can still be applied if we have access to in-sea effluent dilution technology. This type of wastewater dilution proposed in this study is such that wastewater is diluted before entering the seawater, only consuming higher energy than other methods and does not require sophisticated technology. Therefore, for Iran and the Middle East, where energy is cheaper than in other parts of the world, it can be used to reduce the environmental impact of wastewater. According to the obtained results it requires 1.35, 57.47, 3.42, 2.13 and 0.97 million USD for the control of the amounts of CO_2 that mentioned above. For reduction of mal impacts of RBW, 0.75, 22.79, 1.78, 1.15 and 0.55 million USD respectively are required.

On the basis of the applied results of the model, to reduce the environmental impacts of effluent salinity it is recommended to dilute the desalination brine using intake water before entering seawater for desalination up to 50000 m^3/d. Eventually for 100000 m^3/d water desalination plants and power plants are combined in one place, meaning that using power plant cooling water to dilute the desalination effluent before entering the effluent into the seawater to save the dilution cost. As the pretreatment units are very important determinants in desalination costs, it is suggested that a study should be conducted to evaluate the effects of different pretreatment methods on desalination costs.

The limitations of this study were the non-inclusion of small components of investment and operating costs as well as the non-inclusion of the social dimension of sustainability in the mathematical model as it made the model more complicated.

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Ethical issues

The authors hereby certify that all data collected during the research areas expressed in the manuscript, and no data from the study has been or will be published elsewhere separately.

Competing interests

The authors declare that they have no conflicts of interest.

Authors' contribution

All authors were involved in data collection, analysis, and interpretation. All authors reviewed, refined, and approved the manuscript.

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